

## NUMERICAL INVESTIGATION OF RADIATIVE HEAT TRANSFER IN LASER INDUCED AIR PLASMAS

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### ABSTRACT

Radiative heat transfer is one of the most important phenomena in the laser induced plasmas. This study is intended to develop accurate and efficient methods for predicting laser radiation absorption and plasma radiative heat transfer, and investigate the plasma radiation effects in laser propelled vehicles. To model laser radiation absorption, a ray tracing method along with the Beer's law is adopted. To solve the radiative transfer equation in the air plasmas, the discrete transfer method (DTM) is selected and explained. The air plasma radiative properties are predicted by the LORAN code. To validate the present nonequilibrium radiation model, several benchmark problems are examined and the present results are found to match the available solutions. To investigate the effects of plasma radiation in laser propelled vehicles, the present radiation code is coupled into a plasma aerodynamics code and a selected problem is considered. Comparisons of results at different cases show that plasma radiation plays a role of cooling plasma and it lowers the plasma temperature by about 10%. This change in temperature also results in a reduction of the coupling coefficient by about 10-20%. The present study indicates that plasma radiation modeling is very important for accurate modeling of aerodynamics in a laser propelled vehicle.

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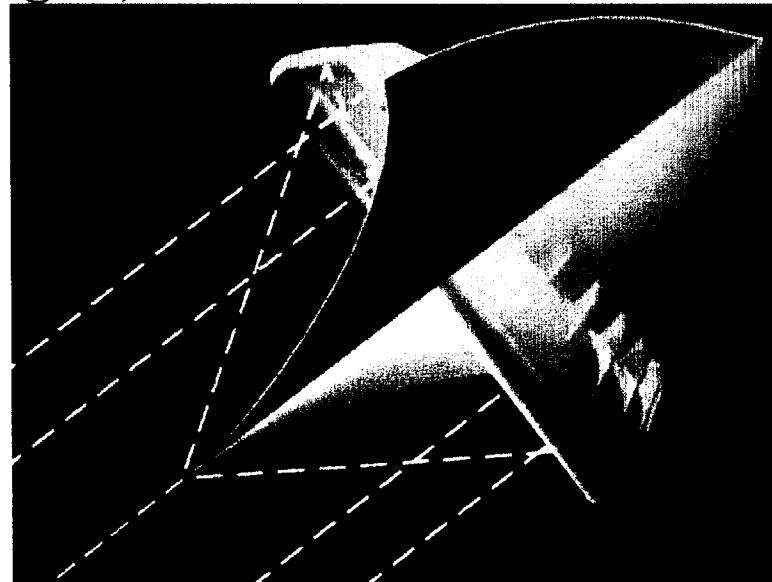
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# **OUTLINE**

- **INTRODUCTION**
- **OBJECTIVES**
- **MATHEMATICAL AND NUMERICAL ANALYSES**
- **RESULTS AND DISCUSSION**
- **SUMMARY**

## **INTRODUCTION**

- **NASA has set out to develop technologies and concepts required for launching small payloads into Earth orbit for a cost of \$100/lb**
- **One potential high pay off approach is laser propulsion which offers advantages of high thrust, good specific impulse, simplicity and reliability of the engine, etc.**



- **An efficient design of laser propelled vehicles requires the detailed understanding of how the detonation waves with different thrust cavity geometry and flight conditions**
- **CFD methods with high-temperature thermodynamics and transient detonation wave capturing capabilities are very useful to provide information for the optimization of the vehicle configuration**
- **Among various phenomena to be modeled, radiative heat transfer is one of the most important also difficult phenomena in laser propelled vehicles**
- **Radiative heat transfer in laser propelled vehicles consists of two different contributions, one from laser radiation absorption and another from nonequilibrium plasma radiative heat transfer**

## **OBJECTIVES**

- **Develop an appropriate numerical model for predicting laser radiation absorption**
- **Develop a detailed numerical model for predicting nonequilibrium plasma radiation**
- **Investigate the effects of plasma radiation on laser propelled vehicles**

## **ANALYSIS**

- **Laser Radiation Absorption**

- **Laser beam is simulated by the geometric optics and it is assumed to consist of a finite number of laser rays**
- **Each ray is traced and its local intensity is calculated by Beer's law:**

$$\frac{dI_i}{ds_i} = -\kappa_l I_i$$

- **Refraction of a laser ray is taken into account and refracted angle is calculated by Snell's law:**

$$n_1 \sin \theta_1 = n_2 \sin \theta_2$$

- **Nonequilibrium Plasma Radiation**

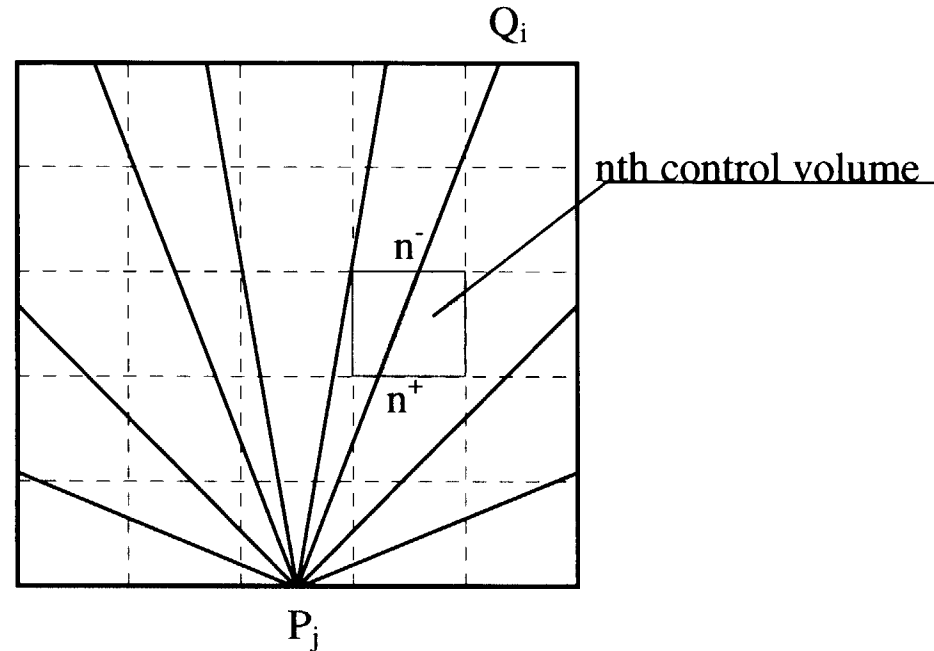
- **Radiative transfer equation (RTE)**

$$\frac{dI_{\omega}(s, \vec{\Omega})}{ds} + \kappa_{\omega} I_{\omega}(s, \vec{\Omega}) = j_{\omega}^e(s)$$

- **Radiation properties model — LORAN code is used to calculate the absorption and emission coefficients from air plasmas**
  - **Numerical method for solving RTE**
    - **Compared to other transport equations, RTE is more difficult to solve because it is a integro-differential equation**



- Many numerical methods such as zonal method, Monte Carlo method, flux method, discrete ordinates method (DOM), discrete transfer method (DTM), etc. have been developed to solve RTE
- DOM and DTM are two of the most widely used methods due to their advantages such as easy formulation, higher accuracy, compatibility with CFD solver
- DTM is selected in this study because the region where RTE is solved can be controlled
- Description of DTM method



- Integrating RTE along a ray:

$$I_{n^+, i \rightarrow j} = I_{n^-, i \rightarrow j} e^{-\kappa \delta s} + \frac{j}{K} (1 - e^{-\kappa \delta s})$$

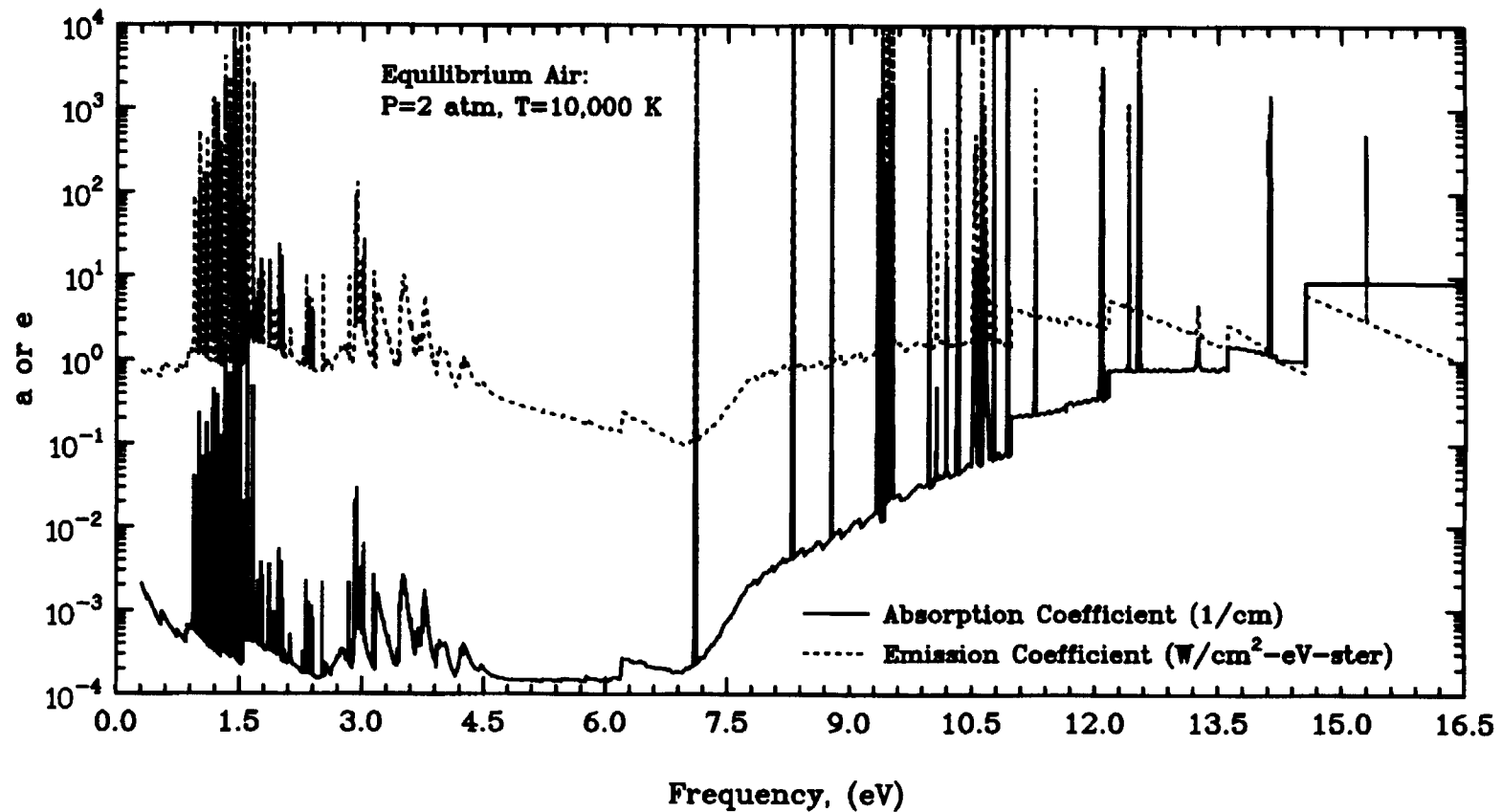
- obtaining radiation source by summing contributions of irradiation rays

$$S_n = \sum_j \sum_i (I_{n^+, i \rightarrow j} - I_{n^-, i \rightarrow j}) D_{j,i} A_j$$

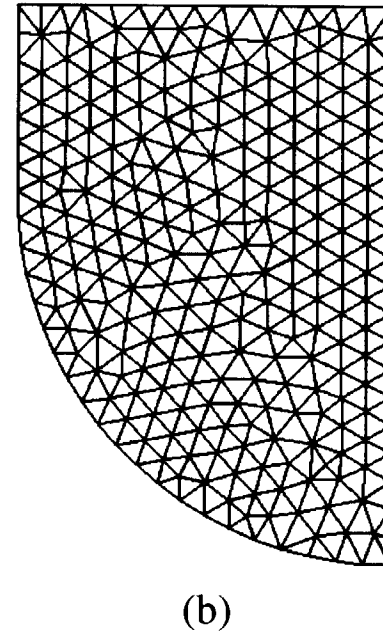
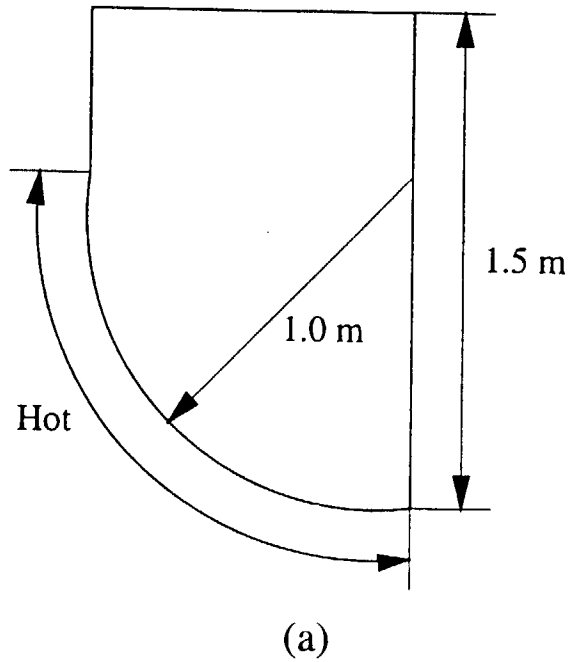
## **RESULTS AND DISCUSSION**

- **Validation of Nonequilibrium Radiation Code**
  - **Validate the modified LORAN code by considering equilibrium air with  $P=2$  atm and  $T=10,000$  K**
  - **Validate the DTM by considering two benchmark problems**
- **Investigation of Plasma Radiative Effects in Laser Propelled Vehicle**

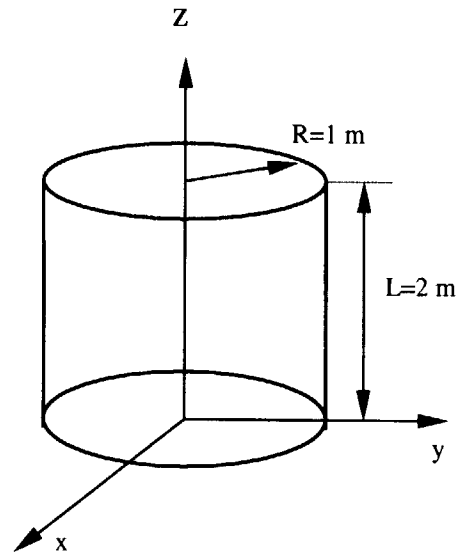
## Absorption and emission coefficients for equilibrium air condition



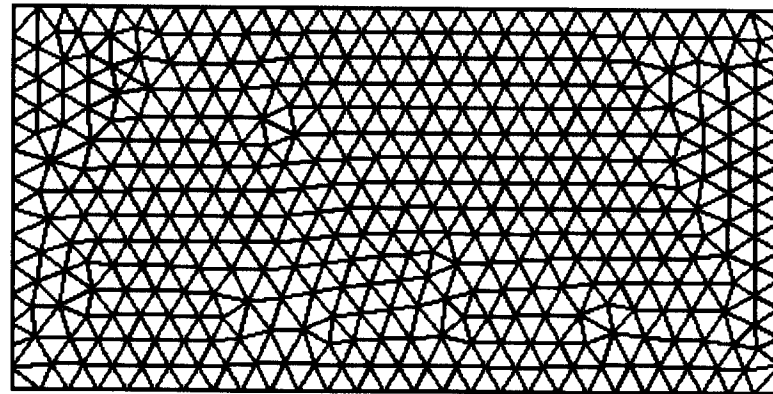
## 2D planar geometry: (a) schematic; (b) unstructured grid



## 2D axisymmetric enclosure: (a) schematic; (b) unstructured grid

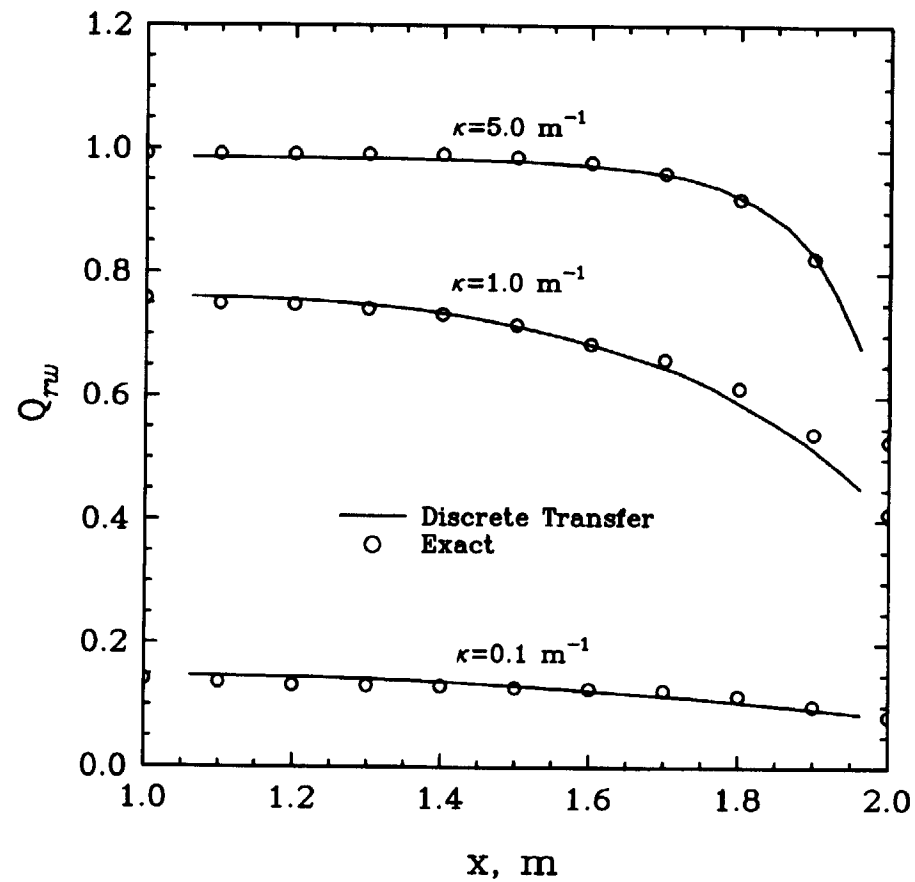


(a)

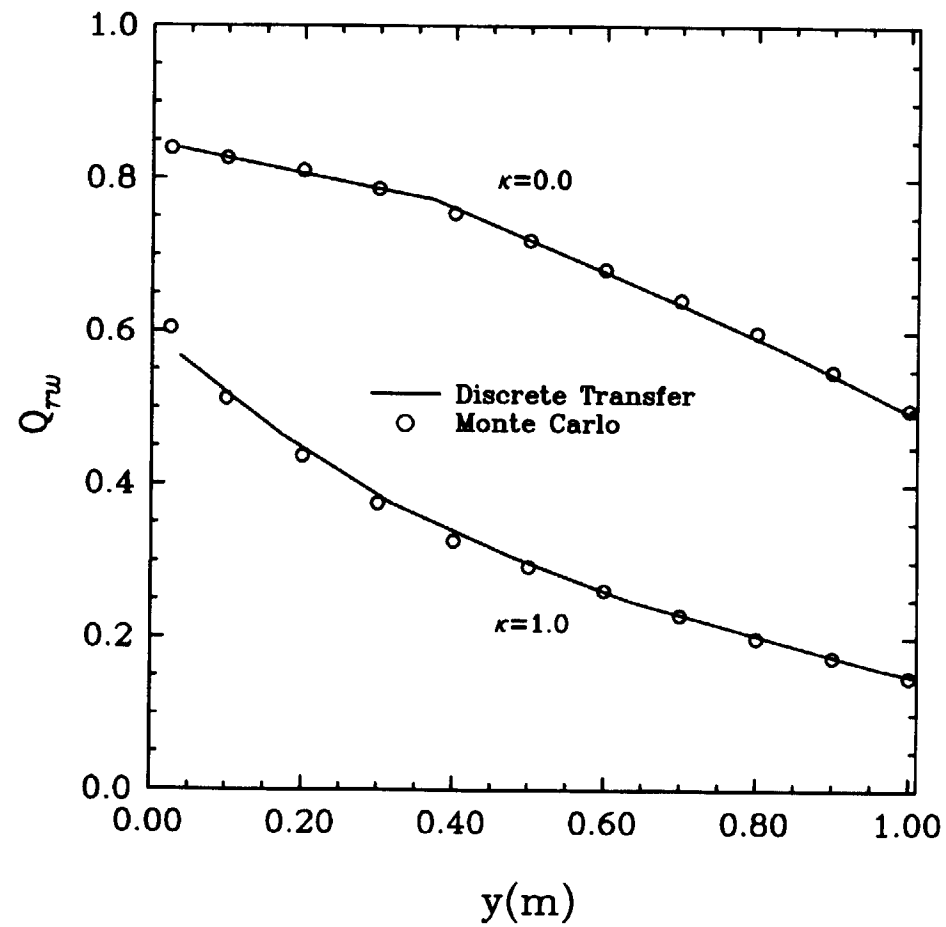


(b)

## Comparison of radiative wall heat flux distributions on the side wall of a cylindrical enclosure



## Comparison of radiative wall heat flux distributions on the right wall

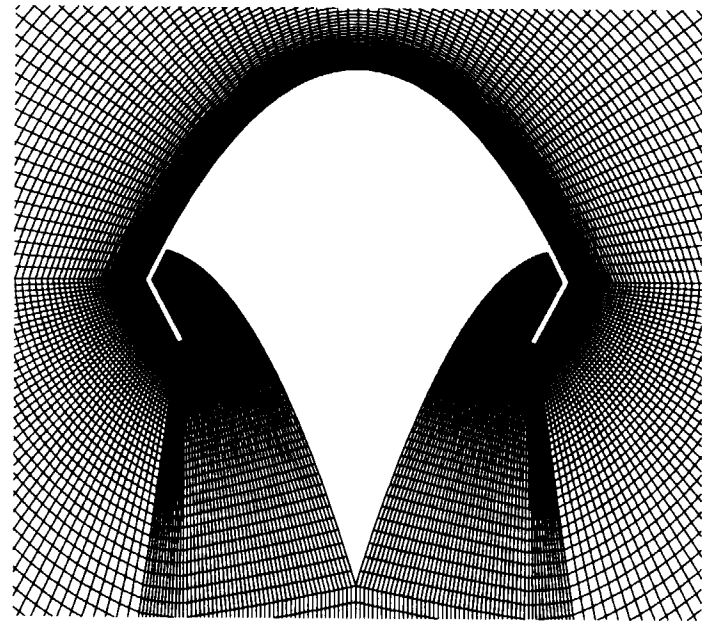
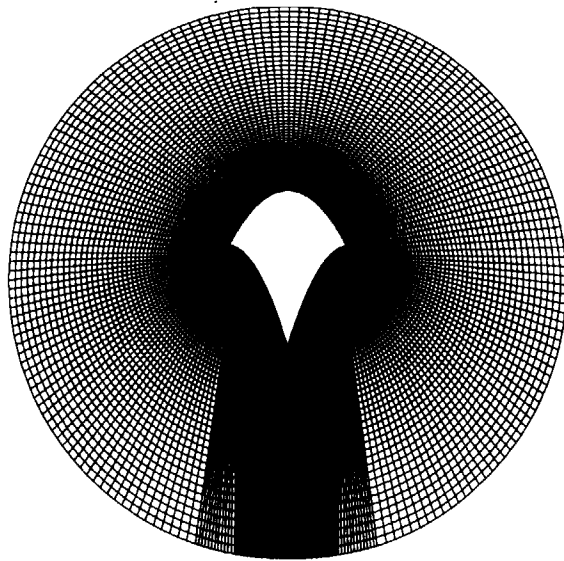




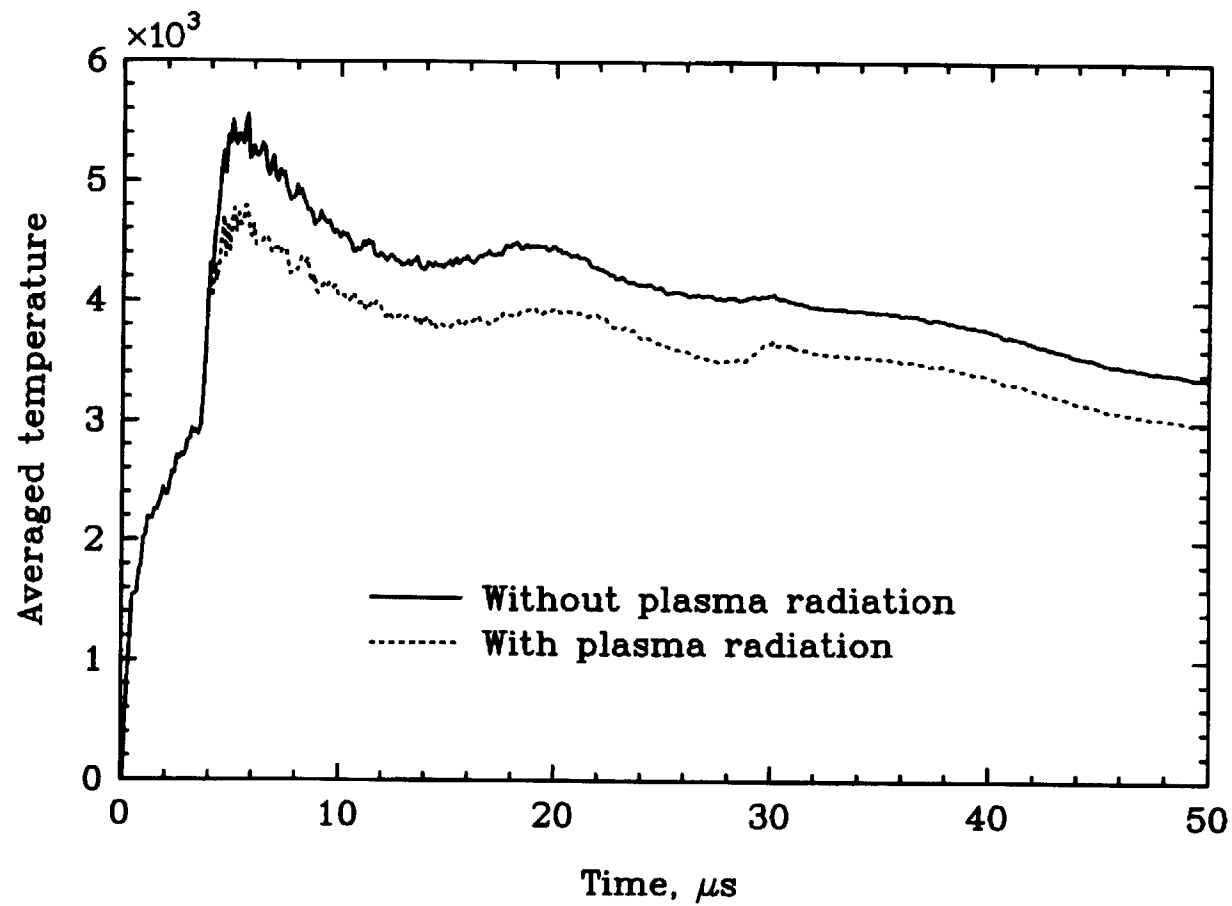
## **Investigation of Plasma Radiative Effects in Laser Propelled Vehicle**

- **Vehicle configuration is based on the Model A of Myrabo's flight tests**
- **The pulsed laser delivers an average energy of 400 J at a pulse width of 30  $\mu$ s**
- **The thermochemical equilibrium is assumed and the total elapsed time considered is 50  $\mu$ s**
- **The results of interest are the averaged temperature in the plasma region, coupling coefficient, and radiative flux distribution along the inner shroud surface**

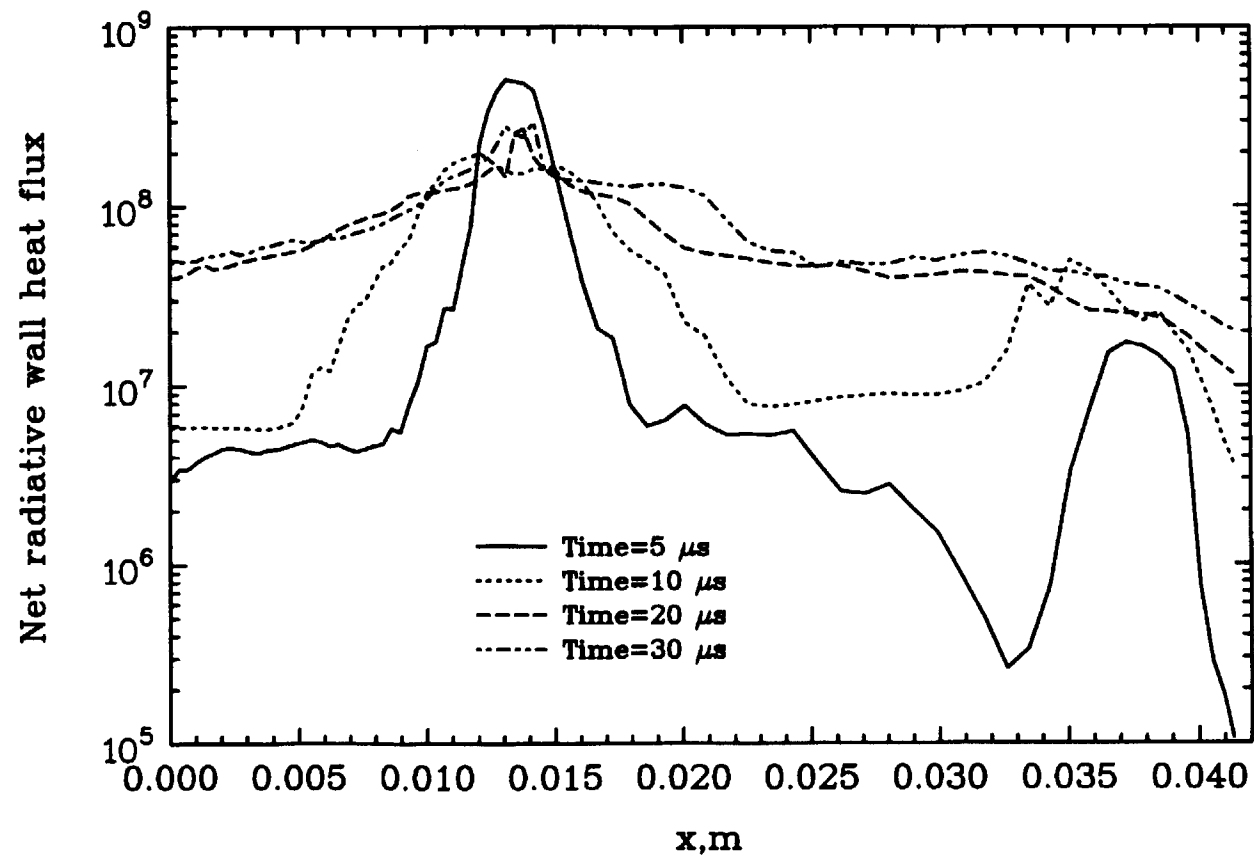
**(a) Layout of a computational grid; (b) a close up view of the grid near the vehicle**



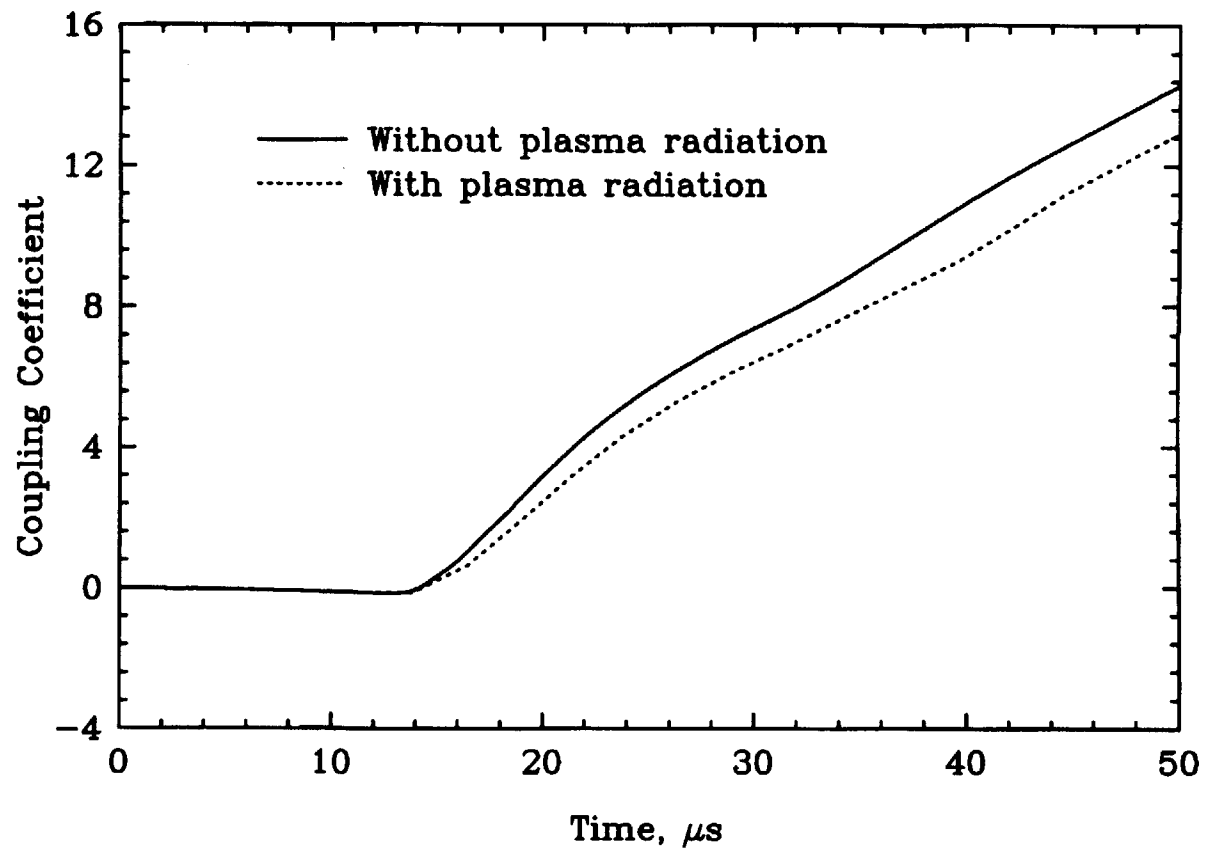
## Comparison of the averaged temperature in the plasma region



## Distributions of the net radiative wall heat flux at different elapsed time



## Comparison of the coupling coefficient



## **SUMMARY**

- **Laser radiation absorption is modeled by the geometric optics along with the Beer's law**
- **Nonequilibrium plasma radiation is modeled by the DTM. The air plasmas properties are predicted by the LORAN code**
- **The present plasma radiation codes has been validated by considering several benchmark problems**
- **The plasma radiative effects in a laser propelled vehicle have been investigated by considering a selected problem. The plasma radiation lowers the plasma temperature by about 10% and reduces the coupling coefficient by about 10-20%.**